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6-20-2019

## Effects of hatchery broodstock collection on adult Muskellunge populations

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# Effects of hatchery broodstock collection on adult Muskellunge populations

## Abstract

Muskellunge *Esox masquinongy* stocking programs throughout North America rely on the collection of wild adult Muskellunge to acquire gametes for hatchery propagation. The process of collecting, transporting, confining, handling, and spawning broodstock Muskellunge may cause mortality that could alter Muskellunge density, size structure, and population survival rates. We used long-term Muskellunge capture-recapture data collected from the Iowa Great Lakes and Clear Lake in northern Iowa, USA to estimate the number and proportion of Muskellunge captured annually and initial mortality rates resulting from broodstock collection. We also evaluated whether Muskellunge apparent survival rates differed between individuals used as broodstock and those that were not captured annually. Finally, we evaluated whether the number of initial mortalities or the number of individuals captured were related to annual population survival estimates. Collectively, 7,010 adult Muskellunge (3,896 males and 3,114 females) captures occurred between 2001-2017 and population densities within a system ranged from 0.11 to 0.39 fish/ha. An average of 33% (range: 13% -76%) of the population was captured during broodstock operations annually. Between 0 and 28 (0.0000 to 0.0191 fish/ha) Muskellunge died at each hatchery annually and more males died than females (total of 150 males and 68 females; 3.9% and 2.2% of captured fish, respectively). However, annual mortalities were generally a low proportion of Muskellunge in the lake (<2%; <0.001 fish/ha). There was some evidence of size selective mortality, particularly for males, where larger individuals (875-975 mm) were more likely to die, but we found no evidence to suggest that broodstock collection affected annual population survival estimates. Muskellunge broodstock mortality appears to act in a compensatory manner with natural mortality, and other sources of population mortality are more likely to have a greater effect on the population.

## Keywords

mortality, program MARK, survival, propagation

## Disciplines

Ecology and Evolutionary Biology | Natural Resources Management and Policy | Population Biology

## Comments

This is a manuscript of an article published as Meerbeek, Jonathan R., and Michael J. Weber. "Effects of hatchery broodstock collection on adult Muskellunge populations." *North American Journal of Fisheries Management* (2019). doi: [10.1002/nafm.10323](https://doi.org/10.1002/nafm.10323). Posted with permission.

Article type : Management Brief

Effects of hatchery broodstock collection on adult Muskellunge populations

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Running title: Effects of Muskellunge broodstock collection

Key words: mortality, program MARK, survival, propagation,

## Abstract

Muskellunge *Esox masquinongy* stocking programs throughout North America rely on the collection of wild adult Muskellunge to acquire gametes for hatchery propagation. The process of collecting, transporting, confining, handling, and spawning broodstock

Muskellunge may cause mortality that could alter Muskellunge density, size structure, and

population survival rates. We used long-term Muskellunge capture-recapture data collected

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/nafm.10323

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from the Iowa Great Lakes and Clear Lake in northern Iowa, USA to estimate the number and proportion of Muskellunge captured annually and initial mortality rates resulting from broodstock collection. We also evaluated whether Muskellunge apparent survival rates differed between individuals used as broodstock and those that were not captured annually. Finally, we evaluated whether the number of initial mortalities or the number of individuals captured were related to annual population survival estimates. Collectively, 7,010 adult Muskellunge (3,896 males and 3,114 females) captures occurred between 2001-2017 and population densities within a system ranged from 0.11 to 0.39 fish/ha. An average of 33% (range: 13% -76%) of the population was captured during broodstock operations annually. Between 0 and 28 (0.0000 to 0.0191 fish/ha) Muskellunge died at each hatchery annually and more males died than females (total of 150 males and 68 females; 3.9% and 2.2% of captured fish, respectively). However, annual mortalities were generally a low proportion of Muskellunge in the lake (<2%; <0.001 fish/ha). There was some evidence of size selective mortality, particularly for males, where larger individuals (875-975 mm) were more likely to die, but we found no evidence to suggest that broodstock collection affected annual population survival estimates. Muskellunge broodstock mortality appears to act in a compensatory manner with natural mortality, and other sources of population mortality are more likely to have a greater effect on the population.

## Introduction

Muskellunge *Esox masquinongy* is a highly prized sportfish throughout its native and introduced range. Consequently, many North American jurisdictions have established specific management objectives to establish and maintain trophy Muskellunge fisheries (Kerr 2011). Because Muskellunge are rarely abundant (Eddy and Underhill 1976), are long-lived

(Casselman and Crossman 1986; Crane et al. *In Press*), and have delayed ages at maturity (ages 3-6; Scott and Crossman 1973; Hanson 1986), they are vulnerable to increases in annual mortality rates due to harvest, catch-and-release angling, and agency sampling (Casselman et al. 1996; McInerny 2014; Shaw et al. 2019). Thus, understanding potential sources of mortality and their effects on populations is an important component of Muskellunge management.

The combination of more restrictive Muskellunge regulations and a catch-and-release philosophy has enhanced Muskellunge fisheries throughout their range (Cornelius and Margenau 1999; Shaw et al. 2019). However, due to an increased demand for this popular sportfish (Perrion and Koupal 2017) and loss of spawning or nursery habitat (Dombeck et al. 1984; Dombeck et al. 1986), artificial propagation and stocking of Muskellunge is needed to establish and maintain Muskellunge populations in many North American jurisdictions (Kerr 2011; Diana et al. 2017; Wagner et al. 2017). Jurisdictions rely on the collection of wild Muskellunge to acquire adequate numbers of adult male and female broodstock for hatchery propagation. Broodstock Muskellunge collection and propagation techniques vary considerably among jurisdictions, but all consist of collecting fish via netting or electrofishing, confining, spawning, and finally releasing fish (Johnson 1958; Jennings et al. 2009; Jennings et al. 2010). Fish exposed to capture experience physical injury and/or physiological stress that may result in initial or delayed mortality (Davis 2002). This additional source of mortality has not previously been examined for broodstock Muskellunge populations but is important to managers attempting to maintain quality fisheries and/or maximize trophy Muskellunge potential.

Few studies have evaluated mortality of wild-caught broodstock fish. Most recently, Blackwell et al. (2018) evaluated female Walleye *Sander vitreus* broodstock mortality in South Dakota, USA lakes by holding stripped and control female Walleye in pens for 5 d post-spawning. Artificial propagation mortality was estimated at 6.8% and was not considered substantial enough to affect female Walleye broodstock populations (Blackwell et al. 2018). However, since Muskellunge are present at low densities in natural populations and a substantial portion may be used as broodstock annually, even slight (<5%) increases in mortality could have serious consequences on long-term Muskellunge population characteristics and stocking requirements. For example, Casselman et al. (1996) suggested that Muskellunge stocking would need to be doubled with a 2% increase in mortality in order to maintain the number of trophy Muskellunge in a population. If broodstock collection methods increase Muskellunge mortality rates, improving broodstock Muskellunge survival may be easier and more effective in sustaining trophy Muskellunge densities than supplementing recruitment through stocking. In addition, Muskellunge broodstock collection occurs at a time period when adult Muskellunge are vulnerable to active and passive capture gears. In a recent study in Wisconsin, the average spring Muskellunge fyke net survey encountered 28% of the adult Muskellunge residing within a lake (Jennings et al. 2010). Consequences of exposing a large percentage of a Muskellunge broodstock population to stresses related to capture and artificial propagation are largely unknown but could have a negative consequence for the population.

Short-term (2 h) gill net sets in March-April are the primary gear used as part of the Iowa Department of Natural Resources (IDNR) Muskellunge broodstock collection efforts. Muskellunge are removed from the nets and transported to hatchery facilities to serve as a broodstock source for continued propagation efforts. Since Muskellunge natural reproduction is limited in Iowa, artificial propagation and stocking is necessary, and sustaining healthy

broodstock populations is paramount to the success and continuation of Muskellunge stocking and management (Meerbeek 2014). Recently, population densities in Iowa's Muskellunge broodstock natural lakes have declined, despite increased stocking rates and low harvest rates (Meerbeek 2014). Managers are concerned whether or not the cumulative effects of numerous stressors due to the artificial spawning operations could be contributing towards declining adult population densities. Our objectives were to use long-term Muskellunge capture-recapture data collected from two broodstock operations in Iowa to 1) estimate the number and proportion of Muskellunge captured annually and 2) estimate initial mortality rates resulting from the broodstock collection effort. We then evaluated 3) if individual Muskellunge captured and brought into the hatchery had different annual survival rates compared to individuals that were not captured annually (individual effect) and 4) if either initial hatchery mortalities (direct effect) or the total number of Muskellunge captured and held in the hatchery (delayed mortality effect) were related to annual Muskellunge population survival estimates to test for additive versus compensatory mortality and determine the potential effects of broodstock collection on population-level mortality.

## Methods

Three connected natural lakes (Spirit, East Okobojo, and West Okobojo lakes; 4,600 ha) are the primary Muskellunge broodstock lakes used by the IDNR for propagation efforts. These three lakes are part of a chain of six natural lakes (Spirit, East Okobojo, West Okobojo, Upper Gar, Lower Gar, and Minnewashta) located in northwest Iowa, USA (Dickinson County) collectively referred to as the Iowa Great Lakes (4,764 ha). Muskellunge were captured in Spirit, East Okobojo, and West Okobojo lakes in March-April (4.4-13.9 °C) during annual broodstock collections (2001-2017) via gill nets (1.8 m × 97.5 m × 6.35 cm bar mesh) as part of the IDNR standard broodstock collection efforts. Specifically, two or three person crews (one to five crews per lake per night) each set 2-3 gill nets for 2 h beginning at

sundown. Gill nets were staked at the shore and set perpendicular to the shoreline at historic locations for each lake. Netting locations and effort (number of net sets) varied among lakes and years due to weather constraints and broodstock needs. At the end of the 2 h set, all nets were checked and broodstock Muskellunge were removed and placed in a large livewell equipped with a flow through system or oxygenated via compressed air. Fish were then transported from the boat livewell to a hatchery truck, transported to the Spirit Lake Fish Hatchery (< 18.0 km from the furthest sampling location), separated by sex (determined by extrusion of gametes), and held in multiple covered indoor concrete raceways (4.8 m × 1.3 m × 1.0 m). On occasion, Muskellunge sex was not determined for fish that died in the gill nets (n = 33; 0.5% of all captures). For these fish, sex was assigned based off year-specific known male:female ratios.

All gill net captured Muskellunge (regardless if used for propagation or not) remained in hatchery raceways until the conclusion of the broodstock operation (between 5 and 18 d).

In the hatchery, female Muskellunge were checked periodically for ripeness and those that were naturally ripe were separated into individual hatchery raceways. To ensure adequate numbers of female Muskellunge broodstock, some female Muskellunge were injected with Common Carp *Cyprinus carpio* pituitary to induce spawning (n = 0-49 each year). Once ripe, female Muskellunge were anesthetized with tricaine methanesulfonate (MS-222) by placing fish in a metal trough (1.5 m × 0.46 m × 0.30 m) filled with approximately 94.6 L of water containing 18 g of MS-222. Once a fish was immobilized, fish were wiped dry with a towel and a towel was placed in the mouth of the Muskellunge to facilitate safe handling of the fish.

Spawning of female Muskellunge required three workers: one worker held the female Muskellunge via the mouth, one worker supported the posterior of fish, and another worker cradled the fish and pressed on the abdomen to expel the eggs. Semen was extracted from male Muskellunge using a similar process, but immobilized fish were placed on a table where



workers pressed on the abdomen to release semen. After spawning, Muskellunge were measured for total length (TL; nearest 2.54 mm) on a rigid/flat measuring board and checked for a Passive Integrated Transponder (PIT) tag. If the Muskellunge was not previously marked, a 12-mm PIT tag was inserted in the cheek. Muskellunge were then placed into a hatchery truck and released back into the lake after gill netting had concluded. Approximately 35 males and 15 female Muskellunge were used as broodstock each year. Muskellunge not used as broodstock were anesthetized, measured, and tagged using the same procedures above. Muskellunge that died during the capture, transport process, or holding period (e.g., initial mortalities) were processed for TL and checked for a PIT tag.

Muskellunge were also captured and retained in Clear Lake (1,467 ha) located in northcentral Iowa (Cerro Gordo County) from 2002-2018 to obtain estimates of population density and size structure. Muskellunge captured from Clear Lake were not used for artificial spawning and propagation but experienced the same field collection and transportation techniques as those collected during broodstock efforts in the Iowa Great Lakes. Specifically, all Muskellunge were collected in March-April via short-term (2 h) gill net sets (same gill net dimensions), placed in a livewell equipped with a flow through system or oxygenated via compressed air, transported from the boat livewell to a hatchery truck, and transported to the Clear Lake Hatchery where they were sexed and held in multiple covered raceways. All Clear Lake Muskellunge were measured and tagged (no anesthetic) and then released back into the lake within 24 h post-capture. Muskellunge mortality resulting from capture or transport was recorded and each fish was checked for an existing PIT tag.

Annual adult Muskellunge density (number  $\geq 762$  mm TL/ha) for the Iowa Great Lakes and Clear Lake were calculated with the Jolly-Seber model (an open population model; Seber 1982) and confidence limits around these estimates were estimated from the method of Manly (1984). The percent of the adult Muskellunge population collected annually and

percent initial population mortality were estimated using Jolly-Seber population estimates, annual catch, and observed (i.e., initial) mortality from each lake. Length-frequency distributions of Muskellunge that were initial mortalities and those that were released alive in Clear Lake and the Iowa Great Lakes were pooled by sex (males, females, and all) and compared via a Kolmogorov-Smirnov (K-S) asymptotic two-sample test using SAS 9.4 (SAS Institute, Inc., Cary, North Carolina;  $\alpha = 0.05$ ).

Individual Muskellunge encounter histories (annual 1=presence or 0=absence data for each individual) during 2001-2017 were analyzed in Program MARK using the live capture-recapture Cormack-Jolly-Seber model to generate maximum-likelihood estimates of annual apparent survival ( $\phi$ ) and detection probability ( $p$ ; White and Burnham 1999). The model estimates apparent survival (hereafter referred to as simply 'survival') which is a combination of emigration and mortality, as these two components cannot be estimated separately. Assumptions regarding tagging of individuals in Cormack-Jolly-Seber and Jolly-Seber capture-recapture models are that tagged individuals are representative of the population of inference, number of fish tagged is known, collecting and tagging fish does not influence survival, no tags are lost and all tags are correctly identified, recaptures and new releases are made during brief time periods relative to the interval being estimated, fates of individuals are independent, individuals in a tagging cohort have an equal probability of survival and recapture probability for a given time interval, and all individuals are available for capture (White et al. 2006).

We tested several hypothesized effects of broodstock capture on adult Muskellunge survival and detection probability. First, we evaluated the effects of lake, sex, years, number of net sets, and number of fish captured on detection probability while retaining the effects of lakes, sexes, and years on survival. Then, we used an annual individual covariate of whether a Muskellunge was captured as a broodstock or not (1=capture or 0=not captured each year of

sampling) to determine if fish that were captured and brought into the hatchery had lower survival compared to fish that remained in the lake within a given year. Finally, we hypothesized that annual survival of the population would be related to either the number of initial mortalities observed in the hatchery (direct effect) or the number of fish captured and brought into the hatchery would be inversely related to annual survival due to a delayed mortality effect associated with the stress of capture and confinement (chronic effect). If the effects of individual or group capture covariates were not supported by the model, compensatory natural mortality or annual variation in environmental factors were more important to annual survival than covariates associated with broodstock capture. Hypotheses were stated in model form in Program MARK and compared using Akaike's Information Criterion corrected for small sample size ( $AIC_c$ ; Burnham and Anderson 2002). Models with lower  $AIC_c$  values were considered more parsimonious and closer to the unknown 'truth'. Akaike weights ( $W_i$ ) were also calculated to address potential uncertainty concerning the selection of the top model (Burnham and Anderson 2002). The variance inflation factor ( $\hat{c}$ ) was estimated and adjusted as 1.187 using the median  $\hat{c}$  procedure in Program MARK. Thus,  $QAIC_c$  (quasi- $AIC_c$ ) was used to evaluate models rather than  $AIC_c$ .

## Results

Between 36 and 160 gill net sets occurred on Clear Lake and 142 to 397 gill net sets occurred annually on the Iowa Great Lakes from 2001 to 2017 (Table 1). A total of 2,467 Muskellunge (1,402 males and 1,065 females) captures occurred during broodstock collection from Clear Lake and 4,543 (2,494 males and 2,049 females) captures occurred from the Iowa Great Lakes from 2001-2017 (Table 1). Muskellunge population densities ranged from 0.18 to 0.39 fish/ha in Clear Lake and 0.11-0.37 fish/ha in the Iowa Great Lakes (Figure 1). Short-term gill net sets were effective in catching a large percentage of the adult Muskellunge population in Clear Lake and the Iowa Great Lakes each year (Figure 1). Average percent of

the Muskellunge population captured ranged from 21.9-76.1% (mean = 38.0%) and 13.0-53.1% (mean = 28.9%) in Clear Lake and the Iowa Great Lakes, respectively (Figure 1).

A total of 83 Clear Lake Muskellunge (53 males and 30 females) and 135 Iowa Great Lakes Muskellunge (97 males and 38 females) died as a result of broodstock collection from 2001-2017 (Table 1). Percent initial mortality based on the number of Muskellunge captured each year ranged from 0.0-12.8% (mean = 3.9%) for males and 0.0-20.8% (mean = 2.3%) for females (Table 1). Broodstock initial population mortality (sexes combined) based on Jolly-Seber population estimates averaged 1.3% (range of 0.0-5.9%) in Clear Lake and 0.8% (range of 0.0-1.9%) in the Iowa Great Lakes (Figure 1). Average initial broodstock Muskellunge mortality was 0.0037 fish/ha (standard error [SE] = 0.0012) in Clear Lake and 0.0018 fish/ha (SE = 0.0004) in the Iowa Great Lakes (Figure 1).

Length-frequency distributions of Muskellunge that died during broodstock collection (initial mortality) and those released alive were significantly different when compared for male and all Muskellunge (K-S range = 2.48-3.83; all comparisons  $P < 0.001$ ) but were not significantly different for female Muskellunge (Clear Lake K-S = 0.83;  $P = 0.50$ ; Iowa Great Lakes K-S = 1.00;  $P = 0.26$ ; Figure 2). Male Muskellunge between 875-975 mm in the Iowa Great Lakes died more often from netting than larger ( $>975$  mm) and smaller fish ( $<875$  mm). Similarly, male Muskellunge in Clear Lake between 875-950 mm experienced higher mortality than their counterparts (Figure 2).

A total of 23 different model combinations were assessed comparing Muskellunge survival and detection probability. The two models that received support ( $\Delta\text{QAIC}_c < 2.0$ ) indicated differences in survival and detection probability between lakes and among years (Table 2). Both models contained the effects of lake and year on both survival and detection probability but the most supported model had an interaction effect between lakes and years

whereas the second most supported model ( $\Delta\text{QAIC}_c = 0.91$ ,  $W_i = 0.38$ ) indicated an additive effect between lakes and years. In the most supported model, Muskellunge detection probability was higher for Clear Lake compared to the Iowa Great Lakes ( $\beta_{\text{CL}} = 1.14$ , 95% CI = 0.73 to 1.53). Annual estimates of detection probability were generally high, ranging from 0.161 to 0.680 in Clear Lake and from 0.030 to 0.450 in the Iowa Great Lakes (Figure 3).

The most supported model also indicated that survival of Muskellunge in Clear Lake was higher than in the Iowa Great Lakes, although the slope of the effect did not differ from 0 ( $\beta_{\text{CL}} = 0.49$ , 95% CI = -0.31 to 1.38). Survival rates also varied annually in both systems, ranging from 0.578 to 0.968 in Clear Lake and from 0.590 to 0.947 in the Iowa Great Lakes (Figure 3). However, there was no evidence that survival of Muskellunge captured and taken to the hatchery (Hatchery capture) had lower annual survival compared to individuals not captured within a given spring ( $\Delta\text{QAIC}_c > 44.50$ ,  $W_i = 0.00$ ) or that the number of Muskellunge captured and taken to the hatchery (Number captures:  $\Delta\text{QAIC}_c > 44.70$ ,  $W_i = 0.00$ ) or the annual number of broodstock mortalities (Hatchery morts:  $\Delta\text{QAIC}_c > 39.00$ ,  $W_i = 0.00$ ) affected annual survival of the population (Table 2).

## Discussion

Successful Muskellunge stocking programs require collecting broodstock from wild populations. It is important that this process does not have long-term deleterious effects on Muskellunge survival rates. In our study, between 0 and 28 (0.0000 to 0.0191 /ha) Muskellunge died each spring at each hatchery and more males died than females (total of 150 males and 68 females; 3.9% and 2.2% of captured fish, respectively). However, any mortalities of large apex predators can be concerning, as they are typically low density populations where even low mortality may have adverse population effects (Casselman et al. 1996; Shaw et al. 2019). High mortality of female Muskellunge as a result of broodstock

collection could truncate the age and size structure of the population, reduce spawning stock biomass, and influence trophy management objectives (Conover and Munch 2002). However, we found that annual hatchery mortalities were a very low proportion of Muskellunge in the lake (<2% in 30 of 33 lake years). There was some evidence of size selective mortality, where larger individuals (875-975 mm) were more likely to die, but we found no evidence to suggest that broodstock collection affected annual population survival estimates, suggesting compensatory mortality processes. Thus, spring Muskellunge broodstock collection appears to be a viable method for acquiring gametes for hatchery production without adversely affecting adult populations.

A large portion of Muskellunge populations in both lakes were captured on an annual basis, creating the potential for broodstock collection to adversely affect the populations. In this study, we captured an average of 33% of the population, but up to 76% of the population in some years. Comparatively, approximately 28% of the adult Muskellunge population was captured annually in Wisconsin (Jennings et al. 2010). High capture probability of Muskellunge in shallow waters during the spring with gill nets is likely a result of spawning behaviors that increase fish movement and duration (about 5-10 d) of shallow water vulnerability (Dombeck 1979; Strand 1986; Gillis et al. 2010). However, we found no evidence to suggest that broodstock collection affected annual survival estimates of individuals captured or that the number of Muskellunge captured or initial mortalities affected annual population survival estimates in either system. Thus, our results indicate that broodstock mortality may be acting in a compensatory manner with natural mortality. Instead, identifying and regulating other sources of population mortality are more likely to have a greater effect on the population compared to reducing broodstock mortality. Survival of Muskellunge has been inversely related to historical harvest (Shaw et al. 2019) and reductions in harvest can reduce mortality rates and increase size and age structure

(Casselman et al. 2017). However, Muskellunge in most of their range, including Iowa, are currently managed with large minimum length limits, most anglers voluntarily practice catch-and-release, and harvest of the species is generally low (Fayram 2003; Margenau and Petchenik 2004; Kerr 2007; Casselman et al. 2017). Alternatively, catch-and-release of Muskellunge may result in either immediate or delayed mortality that may also be affecting populations in some instances. Outside of direct (harvest) and indirect (catch-and-release angling) effects of anglers, little is known regarding factors regulating natural mortality rates of fishes, particularly large bodied fishes such as Muskellunge that are conceivably not susceptible to many sources of natural mortality, such as predation.

Several model assumptions should be considered when interpreting our results. First, estimates presented here are reflective of the population of inference, which in our case is large adult Muskellunge >600 mm. Thus, our results may not be reflective of smaller individuals that were not vulnerable to capture by large-mesh gill nets. Second, our estimates of Muskellunge survival incorporated both mortality and emigration, as these two components cannot be separated in Cormack-Jolly-Seber models. Anecdotal Muskellunge emigration has been observed in both the Iowa Great Lakes and Clear Lake and could be reducing Muskellunge annual survival estimates. We assumed that Muskellunge have similar emigration rates regardless if they were captured annually or not. Thus, Muskellunge emigration could have reduced survival rates but would not affect our ability to detect an effect of hatchery mortality on the population. Finally, other model assumptions include that all marked individuals have the same probability of survival and being recaptured. We tested the assumption of equal survival between captured Muskellunge compared to those that remained in the lake but did not find support for the model, suggesting that we met that assumption and that the process of capturing, transporting, and handling Muskellunge did not affect their survival rates. Extensive springtime sampling occurred throughout both systems

that captured a large percentage of each population. However, sampling on the Iowa Great Lakes did not include three small lakes (Upper Gar, Lower Gar, and Minnewashta) that represent only 3.4% of the surface area of the chain of lakes. If some subset of the Iowa Great Lakes Muskellunge population was predisposed to inhabit these systems, it may have biased our detection probability and survival rate. However, overall detection probabilities were quite high, suggesting that this likely was not an issue.

Beyond the number or proportion of a population captured, broodstock mortality could affect population size structure if differential size-based mortality occurs where larger individuals are more susceptible to mortality. Male mortalities tended to be higher for intermediate (875-975 mm) sized fish. The mechanisms causing increased mortality of intermediate sized male Muskellunge are unknown. Pierce et al. (1994) found that Northern Pike *Esox lucius* catch efficiency in gill nets was related to fish TL and mesh perimeter and maximum catch was obtained at a fish length/mesh perimeter ratios between 3.2 and 4.5. In this study, only one gill net mesh size was used (6.35 cm) and may have been selective for Muskellunge between 875-975 mm. It is possible that male Muskellunge between 875-975 mm were more vulnerable to becoming tangled and thus increasing fish stress and overall mortality rates. Female Muskellunge had a similar, but not significant, pattern of increased mortality at a similar size range in which males died. However, since female Muskellunge do not reach sexual maturity until one or two years later than male Muskellunge (Hansen 1986), there were fewer female fish available for capture that likely influenced our ability to detect significant differences among length classes.

Although Muskellunge broodstock are not used for propagation in Clear Lake, the inclusion of this effort provided a comparison of the effects of hatchery confinement on Muskellunge survival. For example, Muskellunge captured in the Iowa Great Lakes were held in indoor raceways for up to 18 d post-capture to allow gametes to ripen, periodically



examined for ripeness, anesthetized, and then spawned, whereas Clear Lake Muskellunge were held in raceways for less than 24 h and then released. Our study found that exposing broodstock Muskellunge to repetitive handling and prolonged captivity did not result in elevated levels of mortality, either during captivity or after release. We believe that most of the mortality during Iowa's broodstock process occurred during the collection period and that mortality as a result of confining, repeatedly handling, and spawning was insignificant. In our study, large mesh gill nets were used that are known to be effective for capturing Esocids, but gill nets also are known to cause substantial stress and/or mortality if set for long durations, particularly at warmer water temperatures (Woomer et al. 2012; McInerny 2014). In these cases, reducing gill net soaking time or visually observing gill nets for large fish could reduce the amount of time in the net and overall fish stress/initial mortality. In addition, releasing stressed fish immediately post-gill net removal may improve survival of those fishes. Other jurisdictions commonly use large frame fyke nets for Muskellunge broodstock collection (Jennings et al. 2011). Initial mortality and cumulative mortality observed during the collection process for this gear has not been examined, but initial mortalities have been reported to be very low (Mike Habrat, Minnesota DNR, personal communications).

This is the first broodstock study, to our knowledge, that used both known initial mortalities and long-term tagging data to evaluate survival rates of broodstock fish. Our results indicate that Muskellunge mortality as a result of broodstock collection, handling, and spawning does not influence overall population mortality rates and that other sources of mortality are likely more responsible for variations in annual mortality rates. We also found that initial mortality of male Muskellunge was higher than females and that larger male Muskellunge (875-975 mm) were more likely to die than small (<875 mm) males. Although male Muskellunge mortalities likely will not influence population size structure, managers

need to remain concerned about any losses of an apex species and proper capture, handling, and spawning techniques should be used.

### **Acknowledgements**

We thank Scott Grummer, Joe Larscheid, and other staff of Iowa Department of Natural Resources who assisted with data collection. This research was funded in part by the Federal Aid in Sport Fish Restoration program and the Natural Resource Ecology and Management Department at Iowa State University.

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Table 1. Effort (number of 2 hr gill net sets), number of male and female Muskellunge captured, number of male and female Muskellunge that died (morts), and percent of male and female Muskellunge mortality (percent of fish captured that died) observed during broodstock collection efforts in Clear Lake and the Iowa Great Lakes from 2001-2017. Muskellunge were not sampled in Clear Lake during 2001.

Year	Clear Lake							Iowa Great Lakes						
	Number of net sets	Male captures	Female captures	Male morts	Female morts	% Male morts	% Female morts	Number of net sets	Male captures	Female captures	Male morts	Female morts	% Male morts	% female morts
2001	-	-	-	-	-	-	-	158	249	134	0	1	0.0	0.7
2002	144	69	51	1	1	1.4	2.0	224	165	133	2	0	1.2	0.0
2003	129	49	33	1	1	2.0	3.0	142	118	92	5	4	4.2	4.3
2004	130	52	42	5	1	9.6	2.4	177	106	106	11	2	10.4	1.9
2005	84	53	30	4	0	7.5	0.0	216	201	194	12	7	6.0	3.6
2006	102	60	34	1	0	1.7	0.0	183	160	144	7	3	4.4	2.1
2007	160	58	72	0	0	0.0	0.0	319	80	123	2	0	2.5	0.0
2008	102	76	88	1	0	1.3	0.0	210	133	109	1	0	0.8	0.0
2009	78	51	48	0	0	0.0	0.0	252	171	118	0	0	0.0	0.0
2010	36	26	34	1	0	3.8	0.0	181	87	66	3	1	3.4	1.5
2011	36	40	39	2	0	5.0	0.0	248	138	149	5	4	3.6	2.7
2012	36	43	24	5	5	11.6	20.8	378	180	138	23	3	12.8	2.2
2013	36	78	67	0	1	0.0	1.5	345	161	136	3	3	1.9	2.2
2014	108	217	112	2	4	0.9	3.6	261	130	99	9	4	6.9	4.0
2015	126	221	141	19	9	8.6	6.4	396	170	132	8	3	4.7	2.3
2016	144	144	119	5	2	3.5	1.7	397	136	108	3	1	2.2	0.9
2017	108	165	131	6	6	3.6	4.6	324	109	68	3	2	2.8	2.9



Table 2. Cormack-Jolly-Seber model results for 23 model combinations used to estimate adult Muskellunge apparent survival ( $\Phi$ ) and detection probability ( $p$ ) in Clear Lake and the Iowa Great Lakes, Iowa, USA from 2001-2017. Model parameters include the effects of lake, years (t), sex, number of annual hatchery mortalities (Hatchery morts), whether or not an individual fish was captured on an annual basis (Hatchery capture), number of Muskellunge captured annually (Number captured), and number of net sets (Effort).

Model	QAIC <sub>c</sub>	$\Delta$ QAIC <sub>c</sub>	$W_i$	Model Likelihood
$\Phi(\text{Lake} * t) p(\text{Lake} * t)$	13164.80	0.00	0.59	1.00
$\Phi(\text{Lake} + t) p(\text{Lake} * t)$	13165.71	0.91	0.38	0.63
$\Phi(t) p(\text{Lake} * t)$	13171.52	6.72	0.02	0.03
$\Phi(\text{Lake} * \text{Sex} * t) p(\text{Lake} * t)$	13194.36	29.56	0.00	0.00
$\Phi(\text{Lake} * \text{Sex} + \text{Hatchery morts}) p(\text{Lake} * t)$	13203.89	39.09	0.00	0.00
$\Phi(\text{Lake} + \text{Hatchery morts}) p(\text{Lake} * t)$	13206.24	41.44	0.00	0.00
$\Phi(\text{Lake} * \text{Hatchery morts}) p(\text{Lake} * t)$	13206.63	41.83	0.00	0.00
$\Phi(\text{Lake} * \text{Hatchery capture}) p(\text{Lake} * t)$	13209.34	44.54	0.00	0.00
$\Phi(\text{Lake} * \text{Number captured}) p(\text{Lake} * t)$	13209.51	44.71	0.00	0.00
$\Phi(\text{Hatchery morts}) p(\text{Lake} * t)$	13210.77	45.97	0.00	0.00
$\Phi(\text{Lake} + \text{Number captured}) p(\text{Lake} * t)$	13212.72	47.92	0.00	0.00
$\Phi(\text{Lake} + \text{Hatchery capture}) p(\text{Lake} * t)$	13212.73	47.92	0.00	0.00
$\Phi(\text{Hatchery capture}) p(\text{Lake} * t)$	13212.83	48.02	0.00	0.00
$\Phi(\text{Number captured}) p(\text{Lake} * t)$	13212.86	48.05	0.00	0.00
$\Phi(\text{Lake} * \text{Sex} + \text{Number captured}) p(\text{Lake} * t)$	13214.78	49.98	0.00	0.00
$\Phi(\text{Lake} * \text{Sex} * t) p(\text{Lake} * \text{Sex} * t)$	13214.79	49.99	0.00	0.00
$\Phi(\text{Lake} * \text{Sex} + \text{Hatchery capture}) p(\text{Lake} * t)$	13214.99	50.19	0.00	0.00
$\Phi(\text{Lake} * t) p(\text{Lake} + t)$	13225.83	61.03	0.00	0.00
$\Phi(\text{Lake} * \text{Sex} * t) p(t)$	13294.62	129.81	0.00	0.00
$\Phi(\text{Lake} * \text{Sex} + \text{Hatchery morts}) p(\text{Lake} * \text{Number captured})$	13338.61	173.80	0.00	0.00
$\Phi(t) p(t)$	13366.51	201.71	0.00	0.00
$\Phi(\text{Lake} * t) p(\text{Lake} + \text{Number captured})$	13371.85	207.05	0.00	0.00
$\Phi(\text{Lake} * t) p(\text{Lake} + \text{Effort})$	13454.81	290.01	0.00	0.00

Figure 1. Muskellunge annual density within each lake (mean  $\pm$  95% CI) and hatchery mortality (number/ha; top panels) and percent of population captured (mean  $\pm$  95% CI) and percent population initial mortality (mean  $\pm$  95% CI; bottom panels) from Clear Lake (right) and Iowa Great Lakes (left) from 2001-2017.

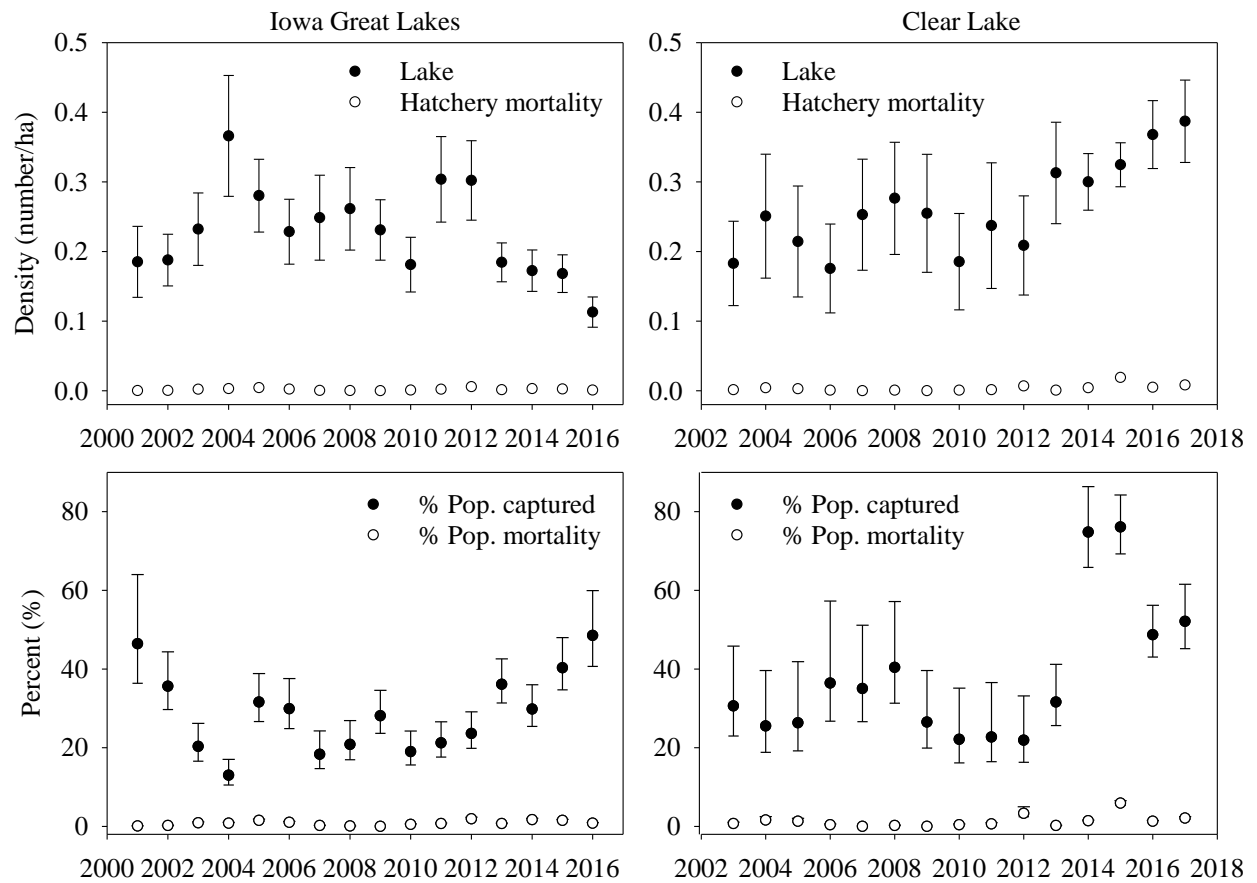


Figure 2. Length-frequency histogram of broodstock female (top), male (middle), and all (bottom) Muskellunge collected (alive) and hatchery mortalities (dead) in Clear Lake (right) and the Iowa Great Lakes (left). A total of 4,498 Muskellunge were captured and released alive and 135 Muskellunge died at the Iowa Great Lakes whereas 2,437 Muskellunge were captured and released alive and 83 Muskellunge died at Clear Lake.

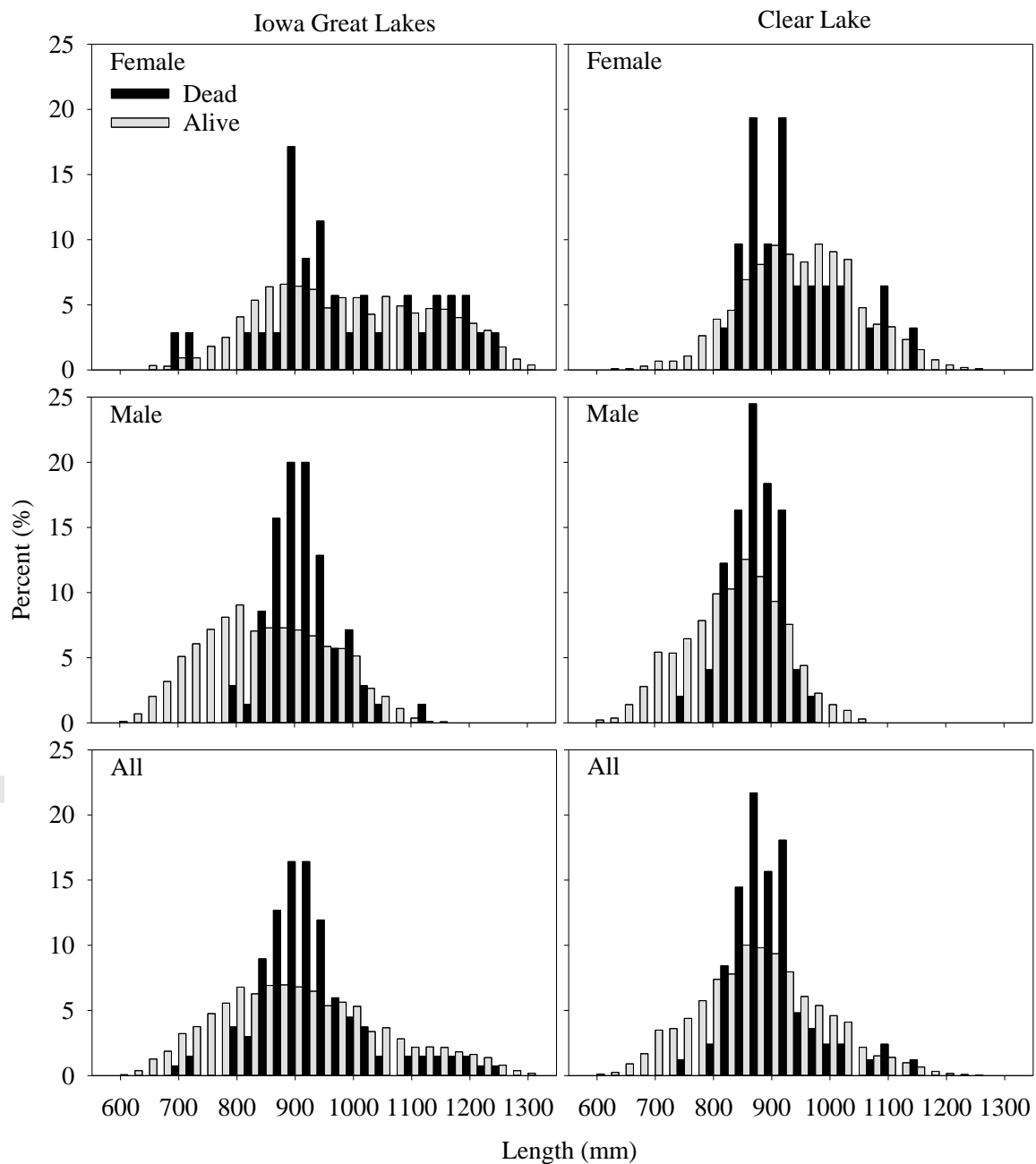


Figure 3. Muskellunge detection probability (top panel) and apparent survival (bottom panel) estimates (mean  $\pm$  95% CI) at the Iowa Great Lakes (IGL; grey bars) and Clear Lake (black bars).

